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# Seabed properties and sediment erodibility along the western Adriatic margin, Italy

A.W. Stevens[a], R.A. Wheatcroft[a,*], P.L. Wiberg[b]

[a]College of Oceanic & Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA
[b]Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904, USA

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## Abstract

During February and June of 2003, selected physical and biological sediment properties were measured at nine mud-bottom sites (11–22 m) along the western margin of the Adriatic Sea. Seabed properties were compared with shipboard measurements of sediment erodibility made at the same sites to gain insight into the physical and biological controls on sediment erodibility operating in the western Adriatic. In addition, spatial patterns of erodibility were compared with long-term records of sediment accumulation in the region to determine if patterns of erodibility were responsible for the discrepancy between sediment sources and sinks on the shelf. Results indicate that sediment erodibility along the western Adriatic Sea varied both in time and space. In the wintertime, sediment in the vicinity of the Po delta (in the northern region) was less easily eroded than to the south. In the summertime, the pattern reversed. The physical characteristics of the seabed including porosity and grain-size were important factors controlling erodibility during the winter, although in a manner opposite to expectations (i.e., higher porosity sediment was less erodible). No relationship between the physical characteristics of the seabed and erodibility was observed in the summer, when it was likely that erodibility was influenced by benthic organisms, especially microphytobenthos. Results of this study suggest long-term sediment accumulation patterns along the western Adriatic Sea are unlikely to be controlled by patterns of erodibility. However, due to several complicating factors, especially along-margin variability in wave energy, the impact of sediment erodibility on long-term patterns of accumulation remains unclear. Further studies that resolve both finer and larger-scale spatial and temporal variability in sediment erodibility and that incorporate year-to-year forcing of the coastal ocean are needed to more accurately resolve the relationship between erodibility and sediment accumulation in the western Adriatic, as well as other coastal environments.


*Keywords:* Sedimentation; Erodibility; Porosity; Continental shelves; Adriatic sea; Italy

## 1. Introduction

The erosion or resuspension of fine-grained sediment is relevant to many aspects of oceanography. For example, to increase the predictive power and accuracy of sediment transport simulations, modelers require direct information on erodibility.

*Corresponding author. Tel.: +1 541 737 3891; fax: +1 541 737 2064.
*E-mail address:* raw@coas.oregonstate.edu (R.A. Wheatcroft).

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Sediment erosion is of importance to civil engineers in the context of structure integrity, navigation, water quality, and shoreline stability (Black et al., 2002). Biologists are interested in sediment erodibility and transport because the physical disturbance caused during resuspension events potentially affects the structure of benthic biological communities (e.g., Hall, 1994). Toxic chemicals, such as heavy metals and chlorinated hydrocarbons (e.g., DDT), are adsorbed onto and desorbed from fined-grained sediment. Hence, the fate of such substances can only be determined through an understanding of sediment erosion and deposition (e.g., Sherwood et al., 2002).

The importance of physical sediment properties such as particle size and water content on erodibility has long been recognized (e.g., Hjulstrom, 1939; Postma, 1967; Einsele et al., 1974). Recent efforts have demonstrated that biologically mediated factors can also be important (e.g., Jumars and Nowell, 1984; Paterson et al., 2000). Accounting for biological effects on sediment erodibility is challenging, however, because whereas physical properties of sediment tend to vary relatively gradually in space and time, the activity and impact of benthic organisms on seafloor properties can vary over small spatial scales and short time scales (e.g., Wheatcroft and Butman, 1997). As a result marine sediments having similar physical properties often respond differently to applied bottom stresses because of the pervasive biological overprint (Jumars and Nowell, 1984).

Erodibility of fine-grained sediment at a given location depends on site-specific factors such as depositional history, consolidation, and post-depositional physical and biological reworking. Because these are seldom known in detail, nor can they be reliably predicted, direct measurements are needed to characterize local erodibility. Measuring sediment erodibility is logistically challenging, thus most direct measurements have been made in estuarine and intertidal environments (e.g., Amos et al., 1997, 2004; Maa et al., 1998), with only a few in open margin environments (e.g., Thomsen and Gust, 2000).

The primary objective of this study was to acquire data on sediment erodibility in a fine-grained continental shelf environment, while at the same time measuring potentially relevant seabed properties (e.g., porosity, grain size, carbonate content, organic carbon fraction). We conducted the study in the western Adriatic Sea as part of the Po and Apennine Sediment Transport and Accumulation (PASTA) project within the EuroSTRATAFORM program (Nittrouer et al., 2004). Within the study area, riverine sediment enters a relatively low-energy coastal environment, flocculates and settles rapidly, forming deposits near the major river mouths (e.g., Nelson, 1970; Boldrin et al., 1988; Fox et al., 2004). However, a portion of the sediment deposited near river mouths is eroded during wave-induced transport events and carried southward along the Italian coast. Evidence from mineralogical studies suggests sediment may be moved 100's of km from its riverine source before eventual accumulation (Ravaioli et al., 2003). The importance of resuspension to sediment dispersal in the Adriatic Sea suggests that, over time, differences in the erodibility of sediment could potentially impact patterns of accumulation along the margin at large (100's of km) spatial scales. Previous studies in the western Adriatic have shown along-margin and seasonal variability in factors that may influence sediment erodibility such as grain-size (Brambati et al., 1983) or carbonate concentration (Ravaioli et al., 2003). However, no attempts have been made to address directly the impact these variables have on the erodibility of fine-grained sediments in the Adriatic.

## 2. Methods

### 2.1. Study area

The study area is in the western Adriatic Sea between roughly 42° and 45°N (Fig. 1). Within this region, sediment input from numerous rivers draining the Alps and Apennines has formed a mud deposit on the western margin of the basin (Correggiari et al., 2001; Cattaneo et al., 2003), with a sand-mud transition at 5–15-m water depth (George, 2003). The largest single source of sediment within the study area, accounting for 13 Mt/yr (~30% of total), is the Po River (basin area of $7 \times 10^4\,km^2$). South of the Po, a series of small rivers ($0.5–3 \times 10^3\,km^2$) with high sediment yields drain the Apennine Mountains, supplying the western Adriatic margin with roughly 22 Mt/yr of sediment (Syvitski and Kettner, 2007). Based on data from a variety of sources, Frignani et al. (2005) have estimated that the majority (~62% of total) of sediment entering the western Adriatic does so north of Ancona (Fig. 1), and that sediment supply decreases markedly to the south (Ancona to Gargano, ~31% of total). In addition to the

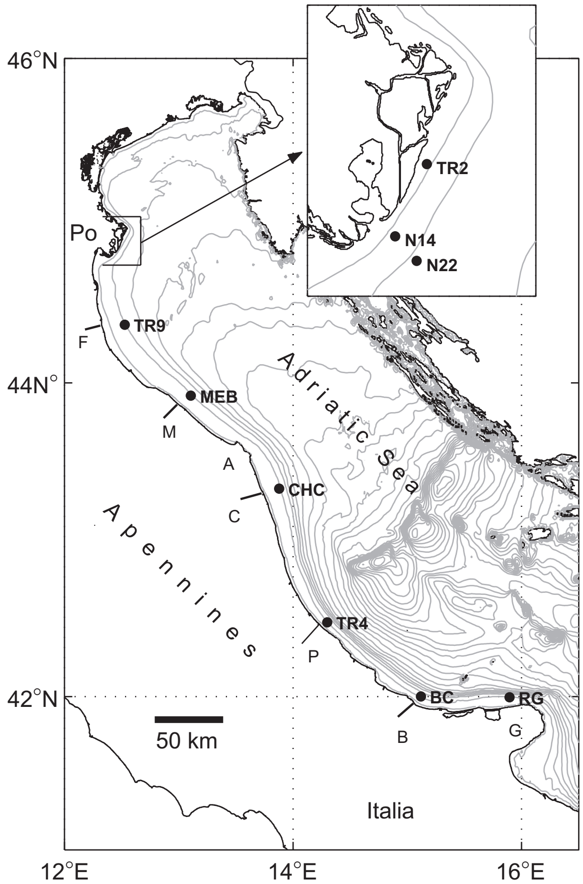


Fig. 1. The location of sampling stations along the western Adriatic Sea. The proximal riverine sources of sediment for each station are the Po, Fiumi Uniti (F), Metauro (M), Chienti (C), Pescara (P), and Biferno (B). The location of Ancona (A) and the Gargano promontory (G) are also shown. Bathymetric contour interval is 10 m.

nonuniform spatial pattern, the temporal delivery of sediment to the Adriatic Sea is heavily influenced by episodic flood events, which occur most frequently in late fall (e.g., Nelson, 1970; Syvitski and Kettner, 2007; Wheatcroft et al., 2006).

Circulation in the Adriatic is characterized by cyclonic (counter-clockwise) movement driven by buoyancy effects and wind patterns (Malanotte-Rizzoli and Bergamasco, 1983). Currents steer Italian river plumes to the south, especially during the winter when northeasterly Bora wind events are common (Poulain and Raicich, 2001). Because of limited fetch and weak tides, the Adriatic is a relatively low-energy environment. Significant wave heights, calculated from data collected between 1999 and 2002 at the Ortona wave buoy (42.4011°N, 14.5339°E), indicate that waves >1.5 m high occur during 8.5% of the 3-year record (George, 2003). Despite the low wave energy, storm waves are capable of causing sediment resuspension in the shallow shelf regions where most of the sediment is accumulating. Fox et al. (2004) concluded that wave resuspension occurred to depths of at least 15 m in the Po prodelta. Further south, off the Chienti River, numerous resuspension events were recorded by a benthic boundary layer tripod at a 20-m site (CHC) between November 2002 and June of 2003 (C. Sherwood, US Geological Survey, unpublished data).

### 2.2. Field sampling

Sediment cores were collected using a hydraulically dampened gravity corer from nine stations along the western Adriatic Sea in February and June of 2003 aboard the R/V Seward Johnson II (Fig. 1; Table 1). Similar to a multiple corer, the hydraulically dampened gravity corer collects a 30–60 cm long by 10.8-cm internal diameter core with a pristine sediment–water interface and intact bottom water. At least six replicate cores were collected at each station. Erosion measurements were made on a minimum of two of these cores; and profiles of sediment resistivity and water content were determined on another two cores. Samples of the uppermost 1 cm of sediment from the remaining cores were taken for determination of grain-size, organic and inorganic carbon, and carbohydrate. All stations were at the same water depth (20 ± 1 m), except stations TR2 and N14, which were 9 m and 14 m, respectively (Table 1). The sites were operationally grouped into two regions that will be referred to throughout the text: the northern region (TR2, N14, N22 and TR9) and the southern region (MEB, CHC, TR4, BC, and RG).

### 2.3. Sediment erodibility

Measurements of sediment erodibility at each station were made using a "Gust erosion chamber" (Gust and Müller, 1999; Thomsen and Gust, 2000). The device comprises a chamber, motor, pump and control unit. The chamber fits directly on the top of a core tube, and uses a rotating plate to generate known and relatively spatially uniform stresses (range of 0.01–0.4 Pa) on the sediment surface (Gust and Müller, 1999; Thomsen and Gust, 2000). Prior to the beginning of each experiment, sediment

Table 1
Station names, water depth, location and distance offshore for each site by region

| Region | Station | Depth (m) | Latitude (N) | Longitude (E) | Distance Offshore (km) | Proximal River | Estimated Sediment Load (Mt/yr) |
|---|---|---|---|---|---|---|---|
| Northern | TR2 | 9 | 44.870 | 12.507 | 1.1 | Po | |
| | N14 | 14 | 44.795 | 12.461 | 2.3 | Po | 13 |
| | N22 | 21 | 44.770 | 12.493 | 6.1 | Po | |
| | TR9 | 19 | 44.363 | 12.527 | 15.7 | Fiumi Uniti | 2.5 |
| Southern | MEB | 19 | 43.920 | 13.106 | 10.0 | Metauro | 0.7 |
| | CHC | 19 | 43.333 | 13.880 | 12.3 | Chienti | 1.4 |
| | TR4 | 19 | 42.480 | 14.299 | 5.2 | Pescara | 1.1 |
| | BC | 21 | 42.002 | 15.118 | 6.5 | Biferno | 2.2 |
| | RG | 19 | 41.996 | 15.895 | 6.8 | N/A | |

The proximal river and estimated annual sediment load, in $10^6$ metric tones, is also listed. Sediment load estimates for the Po and Apennine rivers are from Syvitski and Kettner (2007) and Frignani et al. (2005), respectively.

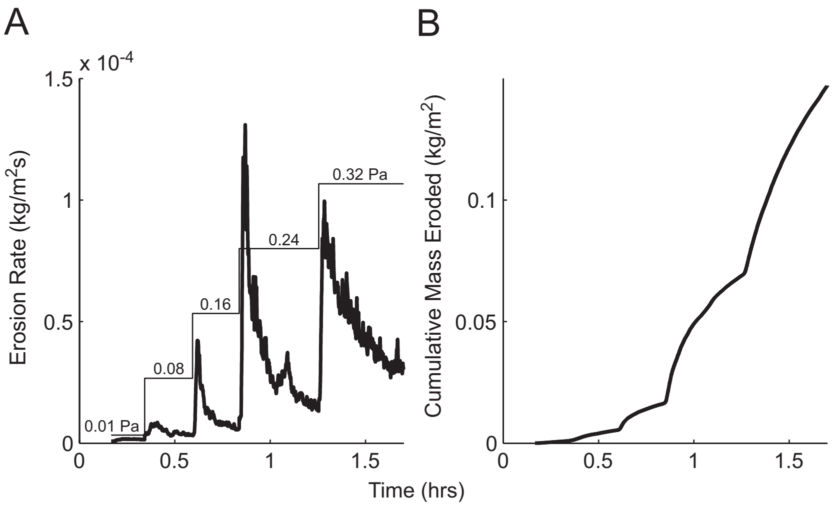


Fig. 2. An example of the output from the erosion chamber. (A) The erosion rate (heavy line) peaks after a step increase in shear stress (light line) and subsequently decreases in a quasi-exponential fashion. (B) Cumulative mass eroded as a function of elapsed time.

within the core barrel was gently positioned to within 10 cm of the core top. Bottom water from the site was pumped into the chamber while an outflow tube brought water from the chamber to a Hach 2100 flow-through turbidimeter and then empties into a 2-L bottle. The erosion tests began with a low applied shear stress (0.01 Pa) to clear minor suspended sediment in the chamber associated with the sample preparation, followed by stress increments of 0.08, 0.16, 0.24, and 0.32 Pa. The stress at each level was typically maintained between 10 and 40 min.

Water that flowed through the turbidity sensor was collected and filtered on 0.47-μm glass fiber filters and then dried and weighed to obtain the mass of eroded sediment. Eroded mass divided by the volume of water filtered gives average suspended sediment concentration for the time interval during which the water sample was collected. Measured sediment concentrations were used to calibrate the turbidity measurements. For stresses that exceeded the critical entrainment shear stress for at least some fraction of the sediment at the bed surface, suspended sediment concentration generally rose relatively quickly, peaked, usually within a few minutes, and then decreased in a quasi-exponential fashion (Fig. 2). When concentration declined to background levels while maintaining a constant shear stress, we assumed that all of the sediment that could be eroded at that shear stress had been removed from the bed, leaving behind sediment with a higher critical shear stress. This assumption allows the cumulative mass eroded as a function of shear stress to be used to approximate the relationship between critical shear stress and mass eroded or depth below the sediment surface if porosity is taken into account (e.g., Sanford and Maa, 2001). Comparison of predicted and measured suspended sediment concentration during the November 2002–June 2003 tripod deployment at Site N14 indicate that the mass eroded vs. critical shear stress relationship determined from the erosion tests can be directly applied in sediment transport calculations (Traykovski et al., 2007).

### 2.4. Seabed characteristics

To characterize the seabed at each station, we measured porosity, bulk density, grain size, organic and inorganic carbon and exopolymeric substances (EPS). High-resolution, vertical profiles of sediment porosity were determined using a resistivity profiler (Wheatcroft, 2002). In this study, two resistivity profiles were measured in the ship's laboratory shortly after a core was brought on deck. Immediately after the resistivity profiles were collected, the overlying water was siphoned off the core and a cut-off 60-cm$^3$ syringe (2.7-cm inner diameter) was inserted into the sediment. The sediment within the syringe was sectioned vertically at 0.5-cm intervals to a depth of 10 cm, and the porosity was determined using wet weight/ dry weight gravimetric techniques.

The relationship between resistivity and porosity in marine sediments has been extensively studied (e.g., Archie, 1942; Andrews and Bennett, 1981; Martin et al., 1991; Wheatcroft, 2002). Archie (1942) related resistivity to porosity using the following equation:

$$FF = \varphi^{-m},$$

where $FF$, the so-called formation factor, is the ratio of sediment resistivity ($R_z$) to the bottom water resistivity ($R_o$), $\varphi$ is the sediment porosity, and $m$ is an empirically derived number that varies according to the physical properties of the sediment. To calculate sediment porosity the formation factor was bin-averaged (0.5-cm intervals) and compared with the water content measurements from the syringe at the same depth. Least-squares regressions were used to estimate $m$. Ideally, to compare porosity with erodibility, data from only the upper few millimeters would be used. However, because the measuring volume extends for ~1.5 mm in the vertical (Wheatcroft, 2002), the resistivity probe senses the overlying water column near the sediment–water interface, thereby leading to an overestimate of porosity in that region. To avoid this complication, the mean porosity corresponding to a depth interval of 0.2–1 cm was used for the comparison with sediment erodibility measurements.

X-radiographs were used to qualitatively characterize the physical structure of the seabed, as well as obtain vertical profiles of bulk density for comparison to the resistivity-derived porosity profiles. Sub-samples for X-ray analysis were taken from either the hydraulically dampened gravity cores or a box core using rectangular polycarbonate X-ray trays. X-ray trays were exposed to a 6.4-s long burst of X-ray radiation at 70 kV and 5 mA using a Lorad LPX-160 X-ray generator. The sample was placed in front of a dPix Flashscan 30 amorphous-silicon imager that captured a 12-bit, gray-scale image with 127-μm pixel size (Wheatcroft et al., 2006). Along with the sample, a calibration bar of known density was placed inside the active area of the imager, and used to establish a relationship between the pixel brightness in the image and bulk density of the calibration bar (by a second-order polynomial regression). Based on this relationship, sediment bulk density ($\rho_b$) was determined (Stevens, 2004).

Triplicate samples for determination of aggregated (or in situ) grain-size were taken from the top 1 cm of cores collected at each station. Grain-size was measured following techniques described in Wheatcroft and Butman (1997). Approximately 1.5 g of untreated, fresh sediment was wet-sieved through two stainless-steel sieves with mesh sizes of 250 and 63 μm within 1 h of core collection. During wet sieving, filtered seawater was passed gently over the sediment using a squirt bottle until particles ceased passing through the sieves. The process is intended to minimize the break-up of natural aggregates. The sediment in each size fraction (>250, 250–63, <63 μm) was vacuum filtered onto pre-weighed 0.8-μm Nucleopore filters. In the lab, the filters were dried in an oven at 60 °C for 24 h and the weight of each size class was determined.

The weight percent of organic and inorganic carbon in surficial sediment was determined following Hedges and Stern (1984). Briefly, samples from the upper 1 cm were oven–dried at 60 °C for 24 h and homogenized using a mortar and pestle. An otherwise untreated sub-sample (10's of mg) of this material was weighed on an analytical microbalance to the thousandth of a milligram and the total carbon determined on a Carlos Erba NA1500 CHN analyzer. A second sub-sample was weighed and treated with concentrated HCl vapor for 24 h to remove inorganic carbon. The organic carbon was measured on this sub-sample on the same CHN analyzer, and the percentage of inorganic carbon was determined by difference between the total and organic carbon fractions.

Exopolymeric substances (EPS) are mucus secretions released by benthic organisms (e.g., diatoms, bacteria, metazoans) that have been shown to stabilize sediment thereby reducing erodibility (e.g., Paterson et al., 2000). EPS is largely made up of carbohydrate polysaccharides (Decho, 1990) and measurements of "colloidal carbohydrate" have been used extensively as a measure of EPS in the marine environment. Solid phase-carbohydrate (colloidal-s) was extracted using the method of Underwood et al. (1995) and quantified using the phenol–sulfuric acid assay (Dubois et al., 1956). After shipboard collection, surface sediment samples were kept refrigerated during their return to the laboratory. In the lab, sub-samples were oven dried at 60 °C and homogenized with a mortar and pestle. Sediment (300–400 mg) was then placed in a test tube with 5 mL of 2.5% saline solution for 15 min to extract the colloidal carbohydrate fraction. During the extraction, the bulk sediment/saline solution slurry was vortex mixed several times. After extraction, the test tube was centrifuged for 15 min at $2200 \times g$ (Earth-based gravities) separating the solid from the supernatant. Concentrations of colloidal carbohydrate were measured in 2-mL aliquots of the supernatant using the phenol–sulfuric acid assay (Dubois et al., 1956). One milliliter of 5% aqueous phenol solution was added followed by 5 mL of concentrated sulfuric acid. The samples were allowed to equilibrate and cool for 30 min. Afterward, the absorbance was measured at 485 nm in a spectrophotometer against several reagent blanks. The amount of carbohydrate in the samples was calculated by comparison to a standard curve produced by analysis of a series of samples with known concentrations of glucose standard solution. Concentrations of colloidal-s carbohydrate in the samples are thus expressed as μg glucose per gram of dry sediment (i.e., glucose equivalents).

## 3. Results

### 3.1. Sediment erodibility

Sediment erosion rates can be expressed in the general form (Sanford and Maa, 2001)

$$E(z,t) = M(z)[\tau_b(t) - \tau_c(z)],$$

where $E$ is erosion rate, $M$ is a coefficient that depends on grain density and porosity, $\tau_b$ is the bed shear stress and $\tau_c$ is the critical shear stress for initial motion. Many researchers have distinguished between two types of erosion (e.g., Amos et al., 1997; Sanford and Maa, 2001). In one case, typical of well-sorted, non-cohesive sediment, $\tau_c$ and $M$ are constant with depth and therefore erosion rates are constant for a given $\tau_b$. In the other case, typical of cohesive sediments, $\tau_c$ and $M$ increase with depth, largely owing to decreases in sediment porosity associated with consolidation, resulting in erosion rates that decrease through time for a constant $\tau_b$. Measured time series of erosion rates from all stations examined in this study are similar to the one from site CHC (Fig. 2), indicative of consolidated sediment with a critical shear stress that increases with depth. The increase in $\tau_c$ limits the mass of sediment that can be eroded at a given $\tau_b$ to the mass above the depth where $\tau_b = \tau_c$. This mass can be represented as the cumulative mass of sediment eroded (Fig. 2B) as a function of shear stress.

The erodibility of sediment along the western Adriatic, expressed as cumulative mass eroded versus applied shear stress (Fig. 3), exhibited appreciable spatial and temporal variability. During February, the cumulative mass eroded at the northern 20-m stations was generally low and did not exceed 0.05 kg/m$^2$ for stresses up to 0.32 Pa. Cumulative mass eroded in February at the southern 20-m stations, was significantly higher with up to 0.24 kg/m$^2$ eroded at site BC (Fig. 3). The pattern of sediment erodibility was quite different in June. Overall, the cumulative mass eroded at the 20-m stations was relatively constant except at the northernmost (N22) and southernmost (RG) sites. The along-margin and seasonal patterns are made clearer by comparing the total mass of sediment eroded between the start of the experimental run and the end of 0.32-Pa shear stress interval, the maximal stress reached in all experiments (Fig. 4). In the winter, the total mass eroded ranged from 0.04 to 0.24 kg/m$^2$, and was generally low for the northern sites and high in the southern region.

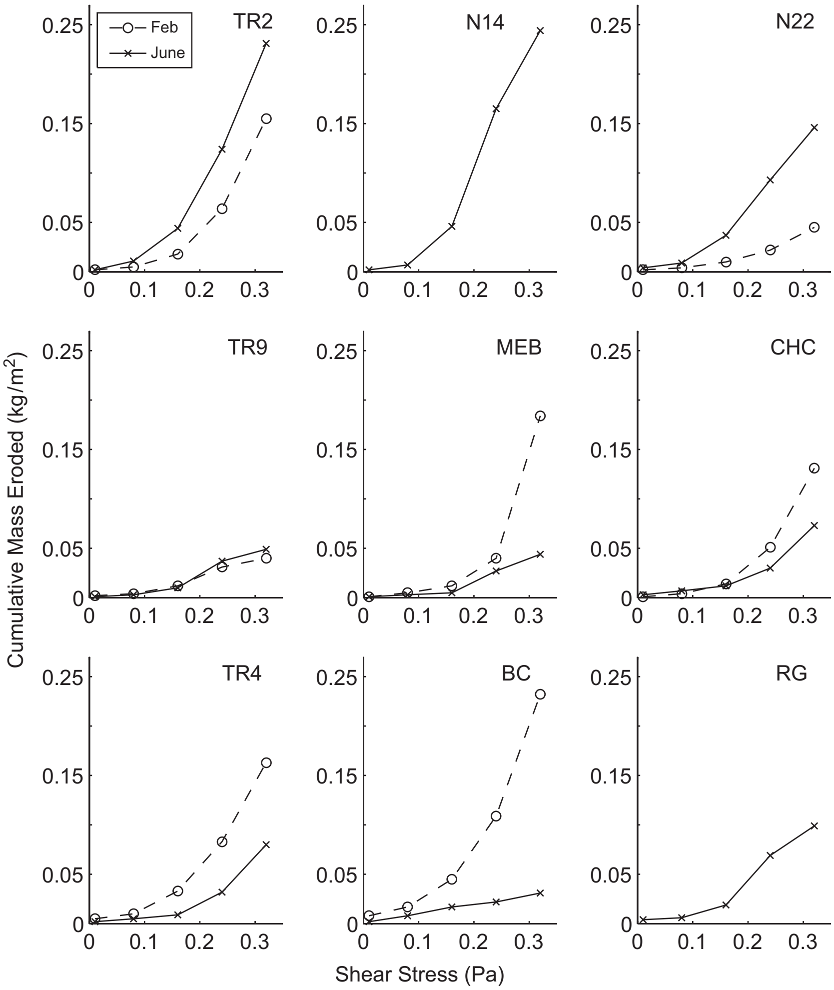


Fig. 3. Plots of cumulative mass eroded versus applied shear stress for each station in February and June. Stations N14 and RG were only sampled in June.

The opposite was observed in June, where the cumulative mass eroded varied from 0.03 to 0.15 kg/m$^2$ along the 20-m isobath (up to 0.24 kg/m$^2$ at the 14-m N14), but was highest for the northern sites and lowest for the southern sites. At three sites, N22, MEB and BC, the cumulative mass eroded was significantly different between February and June (two-way $t$-test, $\alpha = 0.05$).

### 3.2. Seabed characteristics

The mean porosity in the 2–10-mm depth interval along the western Adriatic varies from $>0.81$ near the Po River to $<0.63$ in the southern Apennine region (Fig. 5). Vertical profiles reveal differences in the porosity structure of the upper 1 cm that can be described with an exponential equation of the form:

$$\varphi_z = (\varphi_o - \varphi_\infty)e^{(-\alpha z)} + \varphi_\infty,$$

where $\varphi_z$ is the sediment porosity at a depth $z$,$\varphi_o$ is the porosity at the sediment–water interface, $\varphi_\infty$ is the constant porosity at depth, and $\alpha$ is an empirical attenuation coefficient (Boudreau and Bennett, 1999). In the north (N22), porosity is high at the surface and decreases only slightly with depth (Fig. 5). Further to the south, (e.g., CHC), the surficial porosity is lower and decreases gradually with depth, whereas sediment at station BC displays a steep near-surface decrease and constant low porosity beneath 0.5 cm.

Coefficients describing the porosity profiles at each of the stations for the February and June cruises show considerable variation (Table 2). The porosity at depth, $\varphi_\infty$, tracks the mean porosity and generally decreases along the 20-m isobath from north to south, displaying seasonal variability at some of the sites. The difference between the porosity at the surface and at depth, $\varphi_o - \varphi_\infty$, increases from north to south, but little change between February and June is evident. The attenuation coefficient, $\alpha$, does not have a consistent spatial pattern and is seasonally variable. These results suggest that the seabed becomes increasingly consolidated from north to south. In addition to the spatial variability, there is weak evidence for temporal changes as well (Fig. 6). The surficial

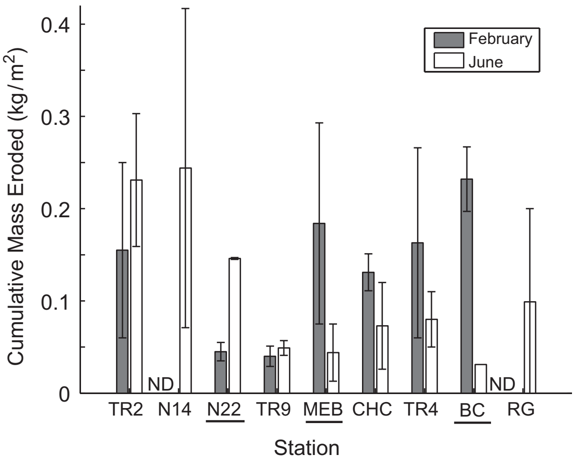


Fig. 4. Cumulative mass (± standard deviation, SD) eroded in February (filled bars) and June (open bars) for shear stresses up to 0.32 Pa. Stations for which there is a statistically significant difference between February and June are underlined (two-way $t$-test, $\alpha = 0.05$). ND = not determined.

Table 2
Parameters describing average porosity profiles (upper 1 cm) for each station sampled during the February and June cruises

| | $\varphi_\infty$ | | $\varphi_o - \varphi_\infty$ | | $\alpha$ | |
|---|---|---|---|---|---|---|
| Station | Feb | June | Feb | June | Feb | June |
| TR2 | 0.67 | 0.58 | 0.36 | 0.35 | 0.53 | 0.11 |
| N14 | ND | 0.69 | ND | 0.35 | ND | 0.29 |
| N22 | 0.77 | 0.76 | 0.21 | 0.23 | 0.20 | 0.41 |
| TR9 | 0.74 | 0.75 | 0.21 | 0.25 | 0.16 | 0.65 |
| MEB | 0.62 | 0.61 | 0.36 | 0.36 | 0.62 | 0.43 |
| CHC | 0.74 | 0.61 | 0.31 | 0.29 | 0.52 | 0.27 |
| TR4 | 0.59 | 0.56 | 0.45 | 0.45 | 0.44 | 0.53 |
| BC | 0.60 | 0.56 | 0.43 | 0.50 | 0.31 | 0.54 |
| RG | ND | 0.57 | ND | 0.47 | ND | 0.37 |

See text for detail. ND = not determined.

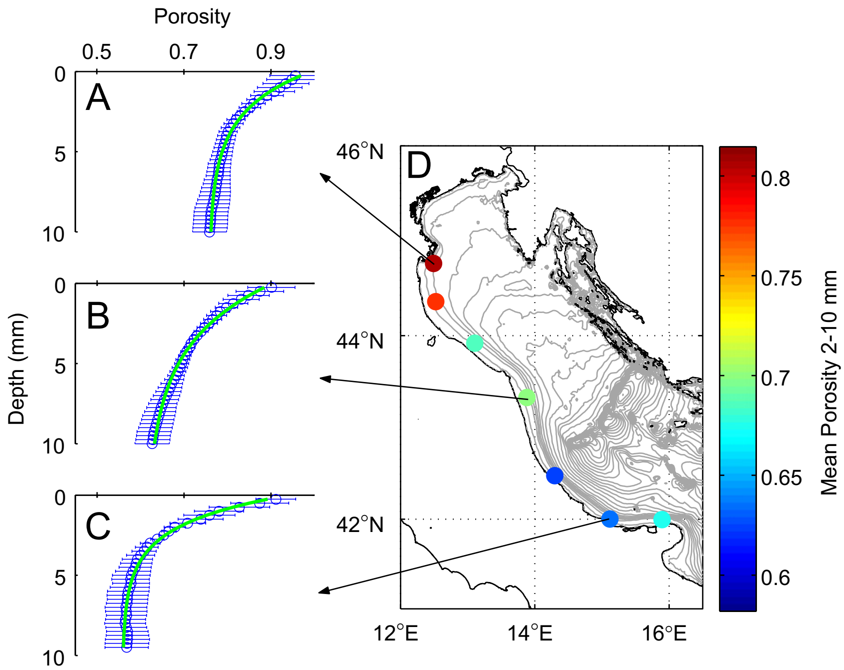


Fig. 5. Vertical profiles of porosity from stations N22 (A), CHC (B) and BC (C). The error bars represent 1 SD of the measurements made on duplicate cores. The green line shows the model fit to the profile (see Table 2). (D) Mean porosity of the 2–10 mm depth interval at the 20-m stations during June 2003.

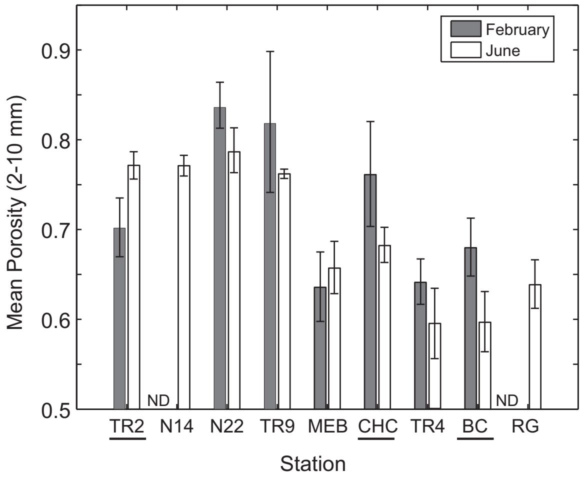


Fig. 6. Mean (±SD) porosity in the 2 to 10-mm depth interval for February (filled bars) and June (open bars). See caption for Fig. 4.

porosity was significantly different at sites TR2, CHC, and BC in February compared to June (two-way $t$-test, $\alpha = 0.05$).

Grain-size data indicate substantial along-margin differences (Fig. 7). The weight percentage of sediment in the >250-μm size class was variable, but in no case exceeded 10% of the total mass. Fine to very-fine sand-sized (250–63 μm) material varied between 6% and 62%, with the lowest values occurring to the north and highest percentages in the three southernmost sites. From north to south, the grain-size distributions are roughly uniform from site TR2 to CHC. A large change in weight percentages of sand and mud occurs between station CHC and station TR4. Between February and June, minor changes in the particle size distributions were observed. At six out of seven stations the amount of mud (<63 μm) was greater in February compared to June, with significant decreases in the mud content between the two sampling dates at only sites CHC and BC (two-way $t$-test, $\alpha = 0.05$).

The weight percentage of inorganic carbon at the sampling sites varied from 2.3% to 4.2% (Fig. 8A), with the lowest values found near the Po. Further to the south, the percentage of inorganic carbon increased to a maximum at site TR4. Between February and June, the inorganic carbon content at TR2 significantly increased (two-way $t$-test, $\alpha = 0.05$). The pattern of bulk organic carbon in the surficial sediments was opposite, high in the northern part of the study area and low to the south, with values ranging from 1.2 to 0.4%

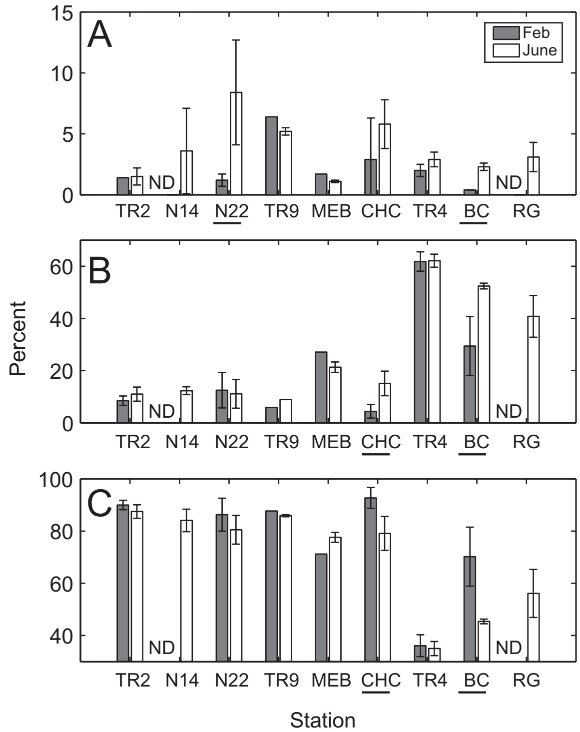


Fig. 7. Aggregated grain-size measurements of three size classes: >250 m (A), 250 μm–63 μm (B) and <63 μm (C). The error bars are the standard deviation of three replicates taken during February (filled bars) and June (open bars). No replicates were collected at sites TR9 and MEB in February. See caption for Fig. 4.

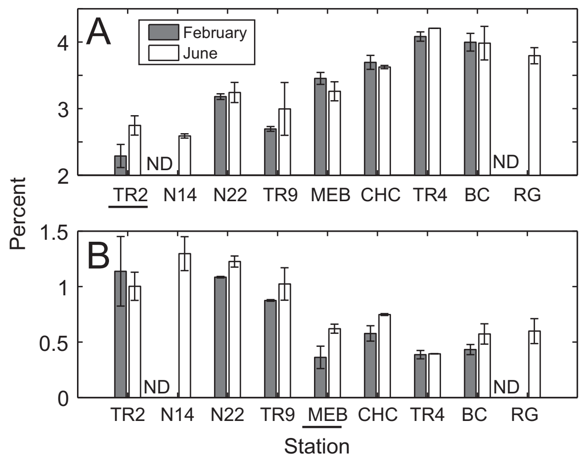


Fig. 8. Histogram of the mean weight-percent (± SD) of inorganic carbon (A) and organic carbon (B) in February and June. ND = not determined. See caption for Fig. 4.

(Fig. 8B). Organic carbon was typically higher in June, but the difference was only statistically significant at site MEB (two-way $t$-test, $\alpha = 0.05$).

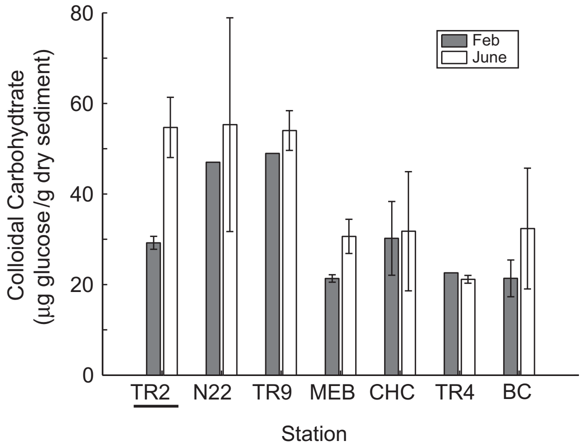


Fig. 9. Mean concentration ($\pm$ SD) of colloidal carbohydrate (µg glucose/g dry sediment) in February (dark bars) and June (white bars). See caption for Fig. 4.

Surface (0–1 cm depth interval) concentration of colloidal-s carbohydrate (see Section 2.4 for explanation of units) ranged from 21 to 55 glucose equivalents (Fig. 9). Although there is considerable variability, the concentration of colloidal carbohydrate generally decreases from north to south. In the summer, mean colloidal carbohydrate concentration at each station was higher than in winter in all but one station. However, due to the small sample size and large variability the seasonal differences were only statistically significant at station TR2 (two-way $t$-test, $\alpha = 0.05$).

## 4. Discussion

### 4.1. Seabed characteristics

The primary objective of this research was to characterize dynamically relevant aspects of the seabed to understand what factors impact sediment erodibility in the western Adriatic Sea. Strong along-margin gradients and, in some cases, weaker temporal changes in grain-size, porosity, organic and inorganic carbon concentrations, and carbohydrate concentration were observed (Figs. 5–9). Before discussing the relevance of these parameters to understanding sediment erodibility, however, it is worthwhile to examine them in terms of internal consistency and potential sources of variability.

Near-surface porosities measured along the western Adriatic margin (Figs. 5 and 6) are broadly similar to fine-scale measurements made using similar devices in sands (e.g., Wheatcroft, 2002) and muds (e.g., Martin et al., 1991). The porosity data are also consistent with vertical profiles of bulk density obtained from X-radiographs on the same cores (Stevens, 2004). As expected, the porosity is highest at the surface and decreases exponentially with depth (e.g., Boudreau and Bennett, 1999). The shape of the near-surface porosity profiles is largely caused by the process of self-weight consolidation (Been and Sills, 1981), but can be modified by bioturbation (e.g., Mulsow et al., 1998). Clear along-margin differences in the shape of the porosity profiles were observed (Fig. 5; Table 2). Martin et al. (1991) found a relationship between carbonate content and the shape of fine-scale porosity profiles, whereby higher carbonate contents led to larger sub-surface porosity gradients. In the present study, a similar correlation was found, whereby southern stations with high inorganic carbon contents reflective of elevated calcium and magnesium carbonate concentrations also had larger sub-surface porosity gradients.

Porosity has long been known to depend on particle size (e.g., Meade, 1966), and this dependence is evident in the present case. Grain-size measurements show a decrease in mud ($<63\,\mu m$) to the south (Fig. 7C) that is reflected in the decrease in mean surface porosity. Higher mean porosity in February at sites CHC and BC (Fig. 6) were also accompanied by significant increases in mud content associated with the emplacement of event beds (see discussion below).

Grain-size also exhibits an along-margin gradient (Fig. 7). The distributions found in the present study roughly follow the previously reported pattern of primary particle size distributions (Brambati et al., 1983); our measurements were made using a different method designed to preserve at least the more resistant aggregates (Section 2.4). Grain-size distributions are controlled by a combination of factors. The particle size distribution of sediment supplied to the seabed by rivers is variable both in time and space. Additionally, wave and current energy winnows away smaller particles and alters grain-size distributions. The relative contribution of each of these factors in creating the observed grain-size distributions is impossible to determine from the available information. For instance, the increase in sand content to the south might be indicative of along-margin differences in the supply of fine-grained sediment from the rivers or could be caused by higher wave and current energy in the south.

Nonetheless, physical factors clearly play a role in the changes in grain-size along the margin.

To a lesser degree, the activity of benthic organisms can also impact grain-size. In order to meet their metabolic needs, benthic deposit feeders must ingest large quantities of sediment and extract the organic matter. As a result, significant quantities of small, organic carbon rich particles are packaged into larger fecal pellets. By comparing the distribution of "aggregated" (i.e., wet-sieving used in this study) versus "disaggregated" (i.e., primary particle) grain-size, information about the amount of aggregates or pellets in each sample can be determined (e.g., Wheatcroft and Butman, 1997). Unfortunately, no information about the disaggregated grain-size distributions in the winter is available, so the percentage of aggregates in the samples in the winter remains unknown. During the summer, separate samples were taken and analyzed for aggregated and disaggregated grain-size. The percentage of aggregates at that time was between 4% and 14% of the total weight of the sample. The highest degree of pelletization in the summer occurred at station N22.

The weight percentage of inorganic carbon in surficial sediment along the 20-m isobath varied from 2.3% to 4.2% (Fig. 8A). The distribution of inorganic carbon in the Adriatic is a function of the carbonate concentration in riverine sediments draining into the western Adriatic, the influence of coastal currents and the contribution of biogenic sources (Ravaioli et al., 2003). The concentration of carbonates in river-derived sediment changes from north to south with calcite varying from 5% in the Po River to as high as 40% in the Chienti River. These differences are in part manifest in the inorganic carbon content of surficial sediment at the 20-m sites (Fig. 8A). Inorganic carbon in the western Adriatic consists primarily of calcium (calcite) and magnesium (dolomite) carbonates. In the northern part of the study area, inorganic carbon is largely made up of dolomite, whereas dolomite contributes a small percent ($< 6\%$) to the inorganic carbon in the southern portion of the study area (Ravaioli et al., 2003). In the present study, the contribution of calcite and dolomite to the total weight percent of inorganic carbon was not quantified, but if the inorganic carbon at stations south of Ancona is assumed to be made up of calcite only, the percentages are roughly equivalent to those reported by Ravaioli et al. (2003).

The weight-percent of organic carbon in surficial sediments displays an along-margin gradient with values ranging from 1.2% in the north to 0.4% in the south (Fig. 8B). These measurements are consistent with those made by other researchers working in the area (Barbanti et al., 1995; Miserocchi et al., 2007). The along-margin organic carbon signal is dominated by the presence of the organic rich sediments originating from the highly industrialized Po River. Seasonal differences in bulk organic carbon were expected owing to higher biological activity both in the water column and in the sediment during the summer. Danovaro et al. (2001) observed increases in organic matter in the northwest Adriatic Sea during the summer as a result of the decomposition of organic matter previously produced by blooms of phytoplankton and benthic microalgae. In the present study, the organic matter content was typically higher in summer, but due to small-scale spatial variability, this increase was only significant at station MEB.

Colloidal carbohydrate values measured during this study are consistently lower than carbohydrate measurements made by Danovaro et al. (2001) during June 1996 and February 1997 in portions of the study area. Oven-drying sediment has been shown to impact the carbohydrate measurement (Underwood et al., 1995) and the sample storage prior to the laboratory analyses was not ideal. Despite the probable artifacts associated with improper sample preservation, all of the samples were treated similarly and thus relative changes between the stations may be valid. The colloidal carbohydrate measurements are consistent with the expected along-margin pattern. Surface (0–1 cm) concentrations of colloidal carbohydrate (Fig. 9) follow a similar pattern as that of organic carbon (Fig. 8B).

### 4.2. Environmental controls on sediment erodibility

Sediment erodibility in the western Adriatic, expressed as cumulative mass eroded as a function of bed shear stress, varies seasonally as well as spatially (Figs. 3 and 4). Consistent with previous investigations of sediment erodibility (e.g., Hjulstrom, 1939; Postma, 1967; Amos et al., 1997, 2004), surficial (2–10 mm) porosity proved to be an important factor controlling sediment erodibility during winter ($r^2 = 0.78$, $p < 0.01$), but not in June ($p > 0.05$) (Fig. 10). The observed relationship between porosity and erodibility during the winter, however, was opposite to expectations based on previous studies (e.g., Amos et al., 1997, 2004).

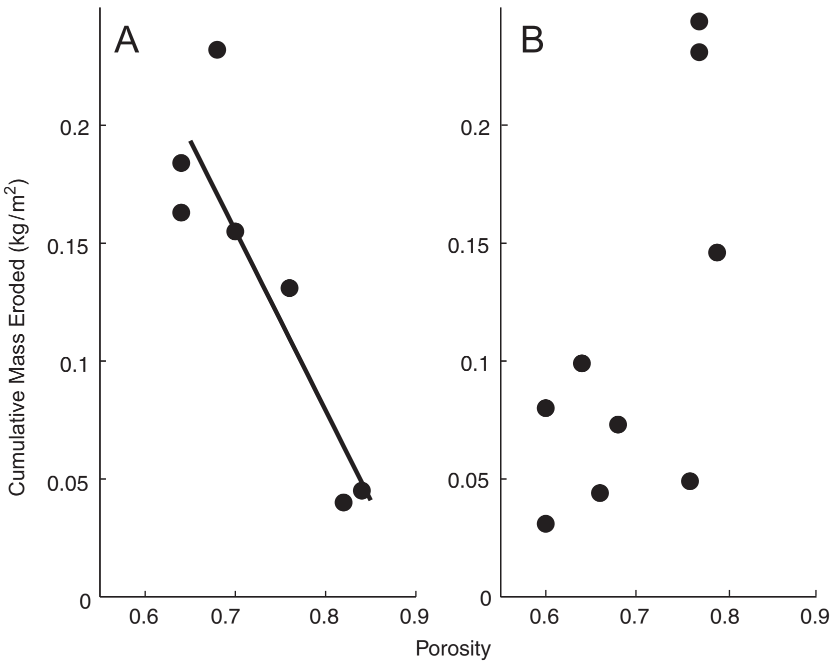


Fig. 10. Comparison between mean surficial porosity (2–10 mm) and cumulative mass eroded at a shear stress of 0.32 Pa for February (A) and June (B). A significant linear relationship was observed in February ($r^2 = 0.78$, $p<0.01$), whereas none existed in June.

Sediment with low porosity was more easily eroded than higher porosity sediment. Our grain-size measurements may help to explain the unexpected direction of the porosity–erodibility relationship during the winter. The highly porous, less erodible surface sediment in the northern part of the study area (e.g., TR2, N14, N22) was also characterized by a small percentage of sand-sized particles (<10%) (Fig. 7). The generally low wintertime erodibility of these muddy, high porosity sediments suggests that inter-particle cohesion may be reducing erodibility or that the presence of sand-sized particles enhances erodibility. Qualitative support for the latter comes from direct observations of large particles rolling along the sediment surface. Such particles may abrade the sediment surface, thereby increasing erosion rates.

The along-margin pattern of erodibility was reversed in June (Fig. 4). The temporal change was most pronounced in the southern part of the study area where sediment erodibility significantly decreased at two stations (MEB and BC). Decreases at the other two southern stations, although not statistically significant, were also observed. The relatively low erodibility during the summer can, in part, be explained by changes in sediment porosity and grain-size. At stations CHC and BC the porosity and mud content were significantly higher in the winter (Figs. 6 and 7), suggesting that freshly deposited material was present on the surface of the seabed. Although no discharge data are available for the study period, river discharge in the central Apennines is known to peak during the late fall and early winter (Syvitski and Kettner, 2007).

X-radiographs taken during February clearly show 1–2 cm of newly deposited sediment at stations CHC and BC (Fig. 11). By comparison, in June, the highly porous surface layer was not present, having either been consolidated or removed between sampling dates. The presence of newly deposited, highly porous material may explain the relatively high erodibility of sediment at those stations during the winter compared to summer. At stations TR4 and MEB, however, no change in the porosity or grain-size was observed, yet the sediment at these stations was less easily eroded in June. A significant increase in erodibility at a northern site (N22), was also not accompanied by a measurable change in the physical properties of the seabed. The lack of correlation between the physical properties of the seafloor (e.g., porosity and grain size) and erodibility during the June sampling period suggests a possible biological control on erodibility.

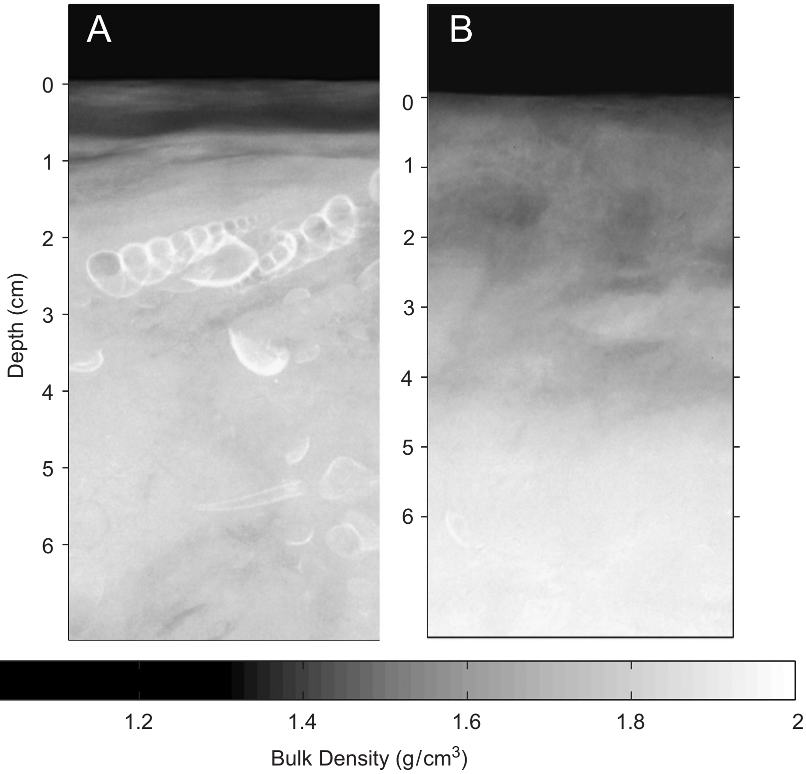


Fig. 11. Digital X-radiographs taken of the seabed at station BC during February (A) and June (B). Approximately 1 cm of low bulk density (1.2 to 1.4 g/cm$^3$), and presumably freshly deposited, sediment was present in February.

Benthic metazoans (i.e., meio-, macro and megafauna) have been shown to both increase and decrease erodibility (Jumars and Nowell, 1984), with perhaps a slight tendency toward the former. For example, de Deckere et al. (2001) used pesticides to eliminate invertebrates from test plots in an estuary and showed that in the absence of macrofauna sediment became more difficult to erode. In the present study, no measurements of macrofaunal abundance or activity were made. However, the density of macrofauna at three sites within the western Adriatic (18-m water depth, 2 in the northern region, 1 in the southern region) was measured in February and June of 1994 by Moodley et al. (1998), and found to be higher in June at all three stations. Thus, the increased erodibility at site N22 in June may have been the result of higher densities and activities of macrofauna. In support of this conjecture, the sediment at station N22 in June had a higher percentage of aggregates compared to the other stations. Higher pelletization is consistent with increased macrofaunal activity at the site relative to other sites along the margin. At the southern stations, sediment erodibility was lower in June suggesting that some other factor was responsible.

Whereas the effect of metazoans on sediment erodibility can be ambiguous, the role of microbes is clear—they lead to stabilization. Through their secretion of extracellular polymeric substances (EPS), bacteria and microphytobenthos (benthic microalgae) have been shown to reduce erodibility (e.g., Tolhurst et al., 2002; Lelieveld et al., 2003). The mucus secretions of organisms are largely composed of carbohydrate polysaccharides (Decho, 1990) and measurements of colloidal carbohydrate have been used extensively as a measure of EPS in the marine environment (e.g., Underwood et al., 1995). If benthic microalgal activity or density were significantly higher in June, then increases in EPS or organic carbon in the surface sediment would be expected. The results are suggestive of an increase in EPS production in the summer (Fig. 9), but are not conclusive, owing to a large degree of within-site variability. Our inability to detect statistically significant differences in EPS concentration between

February and June can largely be attributed to two problems. First, there is likely to be a high degree of small-scale spatial variability in EPS distribution that requires greater replication. Second, benthic microalgae are known to be concentrated in the upper 0.3 cm of the sediment, where light is generally available (MacIntyre et al., 1996). Thus, measurements of EPS should be made at a finer depth scale (i.e., mm's rather than cm's; Paterson et al., 2000).

Although the carbohydrate and organic carbon measurements were inconclusive, previous studies and visual observations during the cruises support the hypothesis that sediment in the southern portion of the study area was colonized by microphytobenthos and thus stabilized during the summer. Danovaro et al. (2001) made carbohydrate measurements at several sites north of Ancona during June 1996 and February 1997 and observed higher carbohydrate concentrations in the top centimeter of sediment in the summer. As part of the same research program, Totti (2003) found thriving populations of microphytobenthos dominated by diatoms at densities of ~9000 cells/cm$^2$ in the upper centimeter of sediment. A final piece of evidence supporting higher densities of microphytobenthos in the summer comes from visual observations of the cores during the June cruise. A reddish-brown color veneer that can be indicative of benthic microalgal populations was observed on the top of many cores, whereas no such veneer was present in February.

### 4.3. *Effect of erodibility on patterns of accumulation*

An apparent paradox exists in the Adriatic Sea whereby high sediment accumulation rates occur north of the Gargano promontory where no proximal riverine sediment sources exist (Cattaneo et al., 2003), and relatively little sediment has accumulated in the vicinity of the Metauro River (station MEB) despite an ample sediment supply (Correggiari et al., 2001).

Because sediment is advected along the Apennine margin during resuspension events, in some cases many times, before accumulating, spatial changes in sediment erodibility could play an important role in determining the long-term pattern of accumulation along the margin. During the energetic transport season (February), measurements along the 20-m isobath indicate that low-erodibility sediment exists at the northern sites and sediment erodibility increases southward (Fig. 4). In the simplest case, in which the bed is exposed to the same time-integrated stress from waves and currents, more sediment would be eroded in the south (e.g., MEB-BC) compared to the northern sites (e.g., TR2–TR9). These data suggest that the mismatch between the sediment accumulation pattern and fluvial sediment inputs cannot be explained by spatial changes in erodibility.

Several factors complicate the relationship between sediment accumulation and erodibility in the Adriatic. First, because of spatial variability in wind patterns and along-margin variation in coastal geometry, wave energy is not uniform. Measurements and models of the northeasterly Bora wind (e.g., Orlic et al., 1994), have shown that there is substantial mesoscale (~50 km) variability in the strength of the Bora winds with a climatological maxima located near the Metauro and Pescara Rivers. Thus, it may be that the thinner high-stand system tract in the vicinity of the Metauro (Correggiari et al., 2001) is caused by enhanced wave energy in that region. Similarly, the impact of the southeasterly Sirocco winds may be lessened in the lee of the Gargano promontory, a conjecture that is consistent with recent model results (C. Sherwood, USGS, unpublished data).

Second, seabed conditions during the study period may not have been representative of the long-term average. In particular, the event beds that were present during February at stations CHC and BC were probably formed by elevated discharges of the Chienti and Biferno Rivers, respectively. Because these beds in particular, and newly deposited sediment in general, have potentially important impacts on erodibility, the timing of sediment deposition prior to the erodibility studies is a key unknown. Moreover, while the discharge of the Apennine rivers was episodic under natural conditions, it is now heavily regulated for flood control and irrigation (Syvitski and Kettner, 2007). As a result, modern depositional conditions may not accurately reflect those associated with the long-term pattern of accumulation.

Lastly, the position of the sampling stations did not coincide with the across-shelf maximum of sediment accumulation along the margin. Although most of the stations were located at 20-m water depth, the depth of maximum accumulation rates varies from the shoreline of the modern Po delta to roughly 50 m near the Gargano peninsula in the south (Correggiari et al., 2001; Frignani et al., 2005). The increased erodibility along the 20-m isobath at the southern stations in the winter may explain why the maximum accumulation rates shift offshore in the southern area by supporting a greater degree of cross-shelf transport and facilitating the movement of sediment into deeper water.

## 5. Summary

Sediment erodibility along the 20-m isobath of the western Adriatic Sea varied both in time and space. In the wintertime, fine-grained sediment in the vicinity of the Po delta (in the northern region) was less easily eroded than to the south. In the summertime, the pattern reversed. The physical characteristics of the seabed including porosity and grain-size were important factors controlling erodibility during the winter. No relationship between the physical characteristics of the seabed and erodibility was observed in the summer, when it is likely that erodibility was influenced by benthic organisms, especially microphytobenthos. Increased macrofaunal activity may have been responsible for the increase in erodibility observed between February and June at station N22 in the north. To the south, lower erodibility in the summer was likely caused by increased inter-particle cohesion and binding of the sediment with exopolymeric substances (EPS) released by microphytobenthos, in addition to changes in sediment properties observed at several sites. Measurable along-margin and seasonal differences as a result of both physical and biological variability of sediment properties clearly underline the need for direct measurements of erodibility to make accurate predictions of fine-grained sediment resuspension in the western Adriatic Sea in particular, and continental shelf settings in general.

Results of this study suggest long-term sediment accumulation patterns along the western Adriatic Sea are unlikely to be controlled by patterns of erodibility. However, due to several complicating factors, especially along-margin variability in wave energy, the impact of sediment erodibility on long-term patterns of accumulation remains unclear. Further studies that resolve both finer and larger scale spatial and temporal variability in sediment erodibility and that incorporate year-to-year forcing of the coastal ocean are needed to more accurately resolve the relationship between erodibility and sediment accumulation in the western Adriatic, as well as other coastal environments.

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